A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
06 (03.11.1; 16.06.1; 19.06.1; 19.37.1; 19.53.1; 19.63.1)

ASTRONOMY AND ASTROPHYSICS
1.2.2008



# An optical and near IR study of the old open cluster NGC 2141*

**G. Carraro[1], S. M. Hassan[2], S. Ortolani[1] and A. Vallenari[3]**

[1] Dipartimento di Astronomia, Universitá di Padova, vicolo dell'Osservatorio 5, I-35122, Padova, Italy
[2] National Research Institute of Astronomy and Geophysics, Helwan, Cairo, A.R.E.
[3] Osservatorio Astronomico di Padova, vicolo Osservatorio 5, I-35122, Padova, Italy
e-mail: carraro,ortolani,vallenari@pd.astro.it

Received ; accepted

**Abstract.** We report on CCD optical ($B$ and $V$ passbands) and near IR ($J$ and $K$ bands) observations in the region of the old open cluster NGC 2141. By combining the two sets of photometry (500 stars in common) we derive new estimates of the cluster fundamental parameters. We confirm that the cluster is 2.5 Gyrs old, but, with respect to previous investigations, we obtain a slightly larger reddening (E(B-V) = 0.40), and a slightly shorter distance (3.8 kpc) from the Sun. Finally we present Luminosity Function (LF) in the V band, which is another age indicator. We provide a good fit for the age range inferred from isochrones by assuming the Kroupa et al. (1993) IMF up to $M_V = 5.0$. We interpret the disagreemt at fainter magnitudes as an evidence of mass segregation.

**Key words:** Photometry:Infrared–Photometry:optical–Open clusters and associations :NGC 2141:individual.

## 1. Introduction

In this paper we continue a series dedicated to the presentation of near-infrared photometry (in $J$ and $K$ passbands) for northern galactic open clusters. We already reported on the very young open clusters NGC 1893 and Berkeley 86 (Vallenari et al 1999), the old clusters Berkeley 17 and Berkeley 18 (Carraro et al 1999a), the intermediate age clusters IC 166 and NGC 7789 (Vallenari et al 2000) and King 5 (Carraro & Vallenari 2000). Here we combine optical $B$ and $V$ and near-infrared $J$ and $K$ photometry for NGC 2141, a faint old open cluster which did not receive much attention in the past.

NGC 2141 is located close to the galactic plane in the antic-enter direction at $l = 198\,^o.75$ and $b = -5^o.79$ , and it is designated also as OCL 487 (Lund 203) and C0600+104 by IAU. Its diameter is estimated to be about $10'$.

A preliminary investigation was conducted by Burkhead et al (1972) who obtained photographic and photoelectric $UBV$ photometry for about 300 stars with the aim of assessing whether the cluster is very old. This study revealed that NGC 2141 is a cluster of late intermediate age, 4.4 kpc distant from the sun, and with a reddening E(B-V)=0.30.

The metal abundance of NGC 2141 has been determined several times in the past. Janes (1979) obtained a value $[Fe/H] = -0.54 \pm 0.42$ from DDO photometry, while Geisler (1987) obtained $[Fe/H] = -0.63 \pm 0.15$ from Washington photometry. Finally, by using medium resolution spectroscopy of six giant stars Friel & Janes (1993) found $[Fe/H] = -0.39 \pm 0.11$

The kinematics of NGC 2141 has been studied by Friel et al (1989) and Friel (1989). This latter study (5 stars) indicates that the radial velocity is $V_r = 43 \pm 6\ km/s$. Individual radial velocities for 15 stars have been obtained by Minniti (1995). This survey has only one star in common with Friel (1989) and the radial velocity estimate is in agreement, suggesting that most of Minniti (1995) stars might probably be cluster non members. Anyway, a much deeper investigation is required to isolate cluster members in NGC 2141.

More recently Rosvick (1995) published optical $VI$ photometry of 3561 stars in NGC 2141 together with $JH$ infrared photometry for a handful of stars. This is the first comprehensive study of NGC 2141. The author infers by comparison with half solar (Z = 0.006) isochrones an age of 2.5 Gyr, a distance of 4.2 kpc and a reddening E(B-V)=0.35.

In this paper we combine IR $JK$ (765 stars) and optical $BV$ (1073 stars) photometry to obtain new estimates

*Send offprint requests to*: G. Carraro (carraro@pd.astro.it)

* Based on observations taken at ESO La Silla and TIRGO.

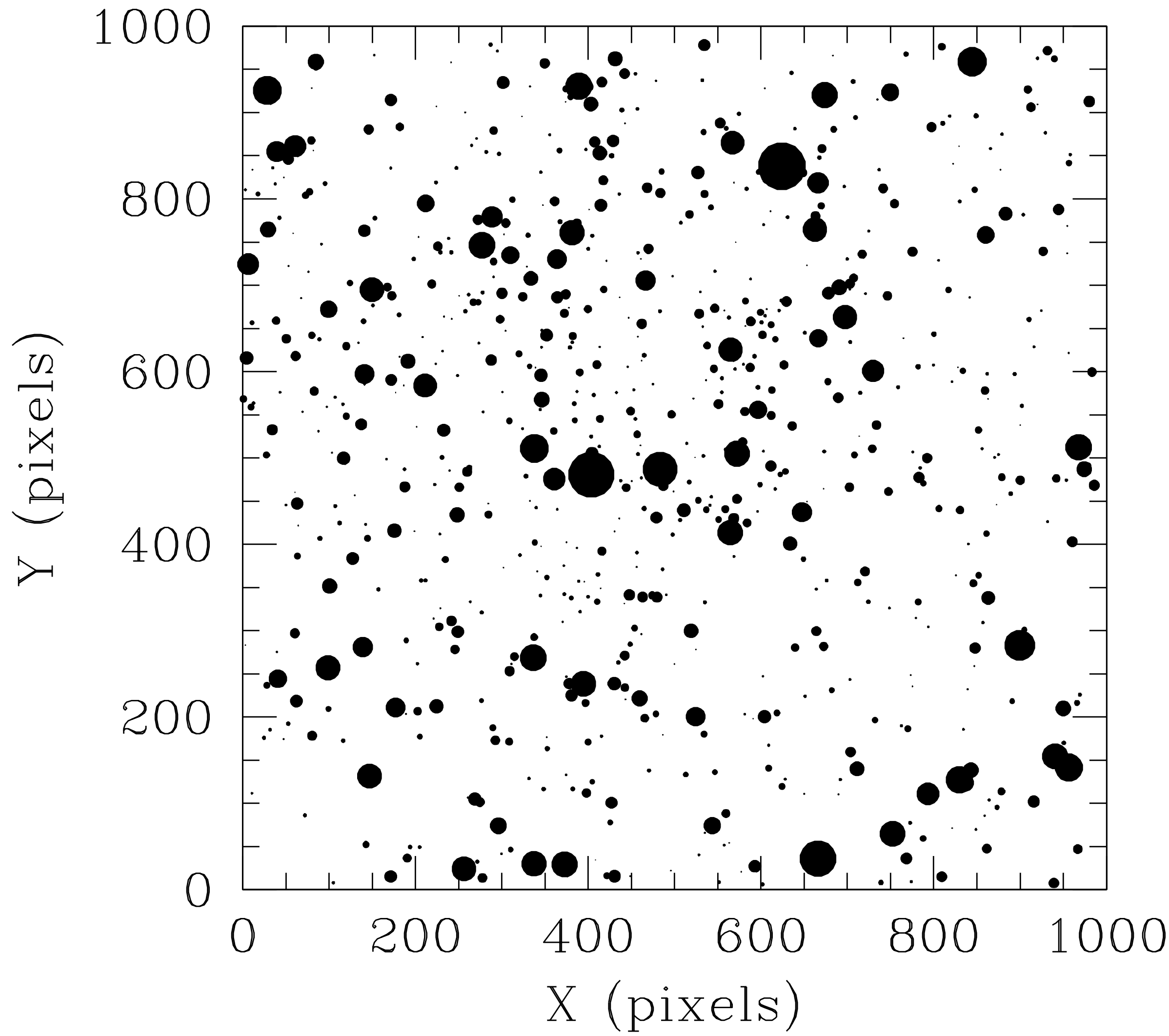


**Fig. 1.** The field covered in the region of NGC 2141 by the optical photometry. The mosaic of the four fields observed in the IR covers almost the same region. North is up, East on the left.

of the cluster fundamental parameters. The layout of the paper is as follows: Section 2 is devoted to the presentation of data acquisition and reduction; Section 3 deals with the morphology of the Color Magnitude Diagrams (CMDs) for different pass-bands; Section 4 concerns the derivation of the cluster metallicity, whereas Section 5 deals with the estimate of color excess. Section 6 is devoted to infer the age and distance, while in Section 7 we discuss the Luminosity Function. Finally our conclusions are summarized in Section 8.

## 2. Observations and Data reduction

### *2.1. TIRGO observations*

J (1.2 $\mu$m) and K (2.2 $\mu$m) photometry of NGC 2141 was obtained at the 1.5m Gornergrat Infrared Telescope (TIRGO) equipped with Arcetri Near Infrared Camera (ARNICA) in October 1997. ARNICA is based on a NICMOS3 256$\times$ 256 pixels array (gain=20 $e^-$/ADU, read-out noise=50 $e^-$, angular scale $=1''$/pixel, and $4' \times 4'$ field of view). More details about the observational equipment and infrared camera, and the reduction procedure can be found in Carraro et al (1999a). Through each filter 4 partially overlapping images of each field were obtained, cov-

**Table 1.** TIRGO observation Log Book

| Cluster | $\alpha$ (2000) | $\delta$ (2000) | Date | Exposure Times (sec) | | Field of view |
|---|---|---|---|---|---|---|
| | | | | J | K | |
| NGC 2141 | 06 02 58.2 | 10 26 39 | Oct, 23, 1997 | 480 | 680 | $7'.5 \times 7'.5$ |

**Table 2.** 2.2m ESO/MPI observation Log Book

| Cluster | $\alpha$ (2000) | $\delta$ (2000) | Date | Exposure Times (sec) | | Field of view |
|---|---|---|---|---|---|---|
| | | | | B | V | |
| NGC 2141 | 06 02 58.2 | 10 26 39 | Dec, 8, 1991 | 1200 | 4200 | $5'.7 \times 5'.7$ |

ering a total field of view of about $7'.5 \times 7'.5$, in short exposures to avoid sky saturation.

The log-book of the observations is presented in Table 1 where the center of the observed field and the total exposure times are given. The night was photometric with a seeing of $1''$-$1.5''$. Fig.1 presents the final mosaic of the 4 frames for NGC 2141 in K passband.

The conversion of the instrumental magnitude j and k to the standard J, K was made using stellar fields of standard stars taken from Hunt et al (1998) list. About 10 standard stars per night have been used.

The relations in usage per 1 sec exposure time are:

$$J = j + 19.51 + k_J \times 1.03 \quad (1)$$

$$K = k + 18.94 + k_K \times 1.06 \quad (2)$$

where $k_J$ and $k_K$ (the extinction coefficients, in magnitude per airmass) are 0.25 and 0.10, respectively. The standard deviation of the zero points of 0.03 mag for the $J$ and 0.04 for the $K$ magnitude. This error is only due to the linear interpolation of the standard stars. The calibration uncertainty is dominated by the error due to the correction from aperture photometry to PSF fitting magnitude. The standard stars used for the calibration do not cover the entire color range of the data, because of the lack of stars redder than $(J - K) \sim 0.8$. From our data, no color term is found for $K$ mag, whereas we cannot exclude it for the $J$ magnitude. Taking all into account, we estimate that the total error on the calibration is about 0.1 mag in both $J$ and $K$ pass-bands (see Vallenari et al 2000 for additional details).

### *2.2. 2.2m ESO/MPI observations*

NGC 2141 was observed with the 2.2m ESO/MPI telescope at La Silla. The focal reducer ESO EFOSC 2 camera was used, equipped with the Thompson UV coated $1000 \times 1000$ pixels CCD ESO # 19. The chip has 19 micron pixel size, corresponding to $0''.34/pixel$ projected on the sky. The total field of view is about $5'.7 \times 5'.7$ . The observations have been carried out in 1991 December 8 (see Table 2 for details.) The night was photometric with an average seeing of $1''.5$. Several standard field stars from Landolt (1992) have been observed during the same night, from which the following color equations have been derived:

$$V = v + 25.75 + 0.05 \times (B - V)$$

$$B = b + 26.11 + 0.21 \times (B - V)$$

After the standard pre-processing, instrumental magnitudes have been extracted using DAOPHOT II and the accompanying ALLSTAR program in the MIDAS environment. Since the field is relatively crowding free, the aperture corrections have been directly computed on the original frames, giving the coefficient within a 0.02 magnitude spread. The final errors in the zero points amount to 0.02 both in $B$ and in $V$. The comparison of 5 stars in common with Burkhead et al (1972) yields:

$$V_{BBH} - V_{CHOV} = 0.01 \pm 0.01$$

$$(B - V)_{BBH} - (B - V)_{CHOV} = 0.02 \pm 0.02$$

where $BBH$ and $CHOV$ refer to Burkhead et al (1972) and the present work, respectively.

We estimated the photometric errors by means of experiments with artificial stars (Carraro & Ortolani 1994), obtaining errors of 0.02, 0.04 and 0.08 at $V = 18$, 19 and 20 mag, respectively. Another estimate of the photometric errors derives from the MS natural width. At the same above magnitude levels we found dispersions in color of 0.11, 0.16 and 0.20. These latter values clearly take into account also the effect of unresolved binaries (see the sequence rightwards of the MS in Figs. 2 and 3) and possible variable reddening.

## 3. The Color Magnitude Diagram

In this section we discuss separately the CMDs obtained from the optical and near IR photometry.

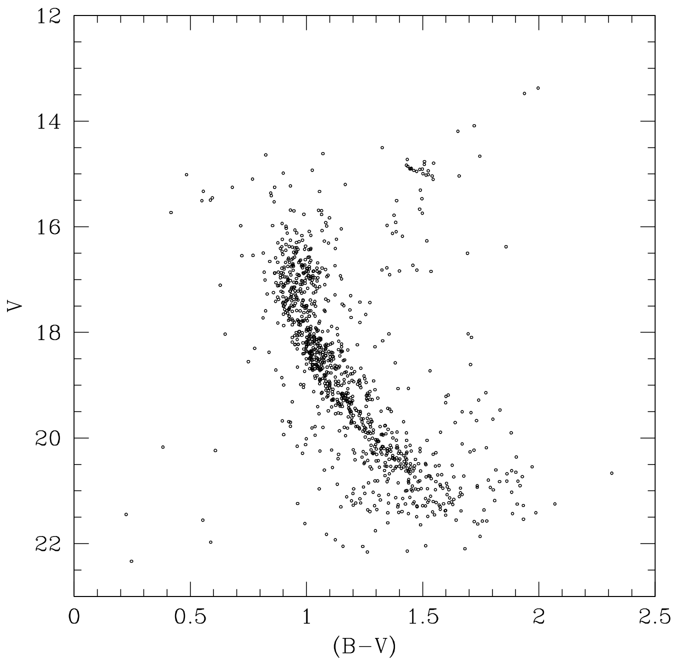


**Fig. 2.** The CMD of NGC 2141 derived from optical photometry.

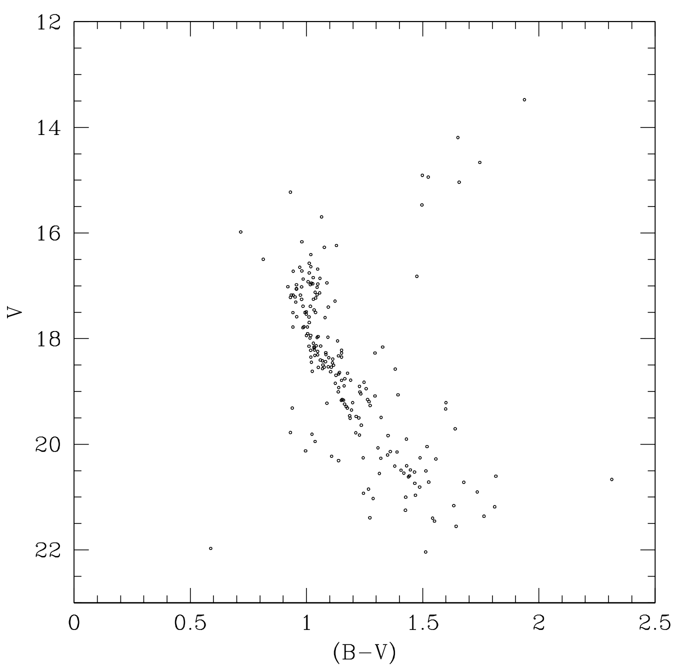


**Fig. 3.** The CMD of NGC 2141 derived from optical photometry by considering only stars within 1.2 arcmin from the cluster center . Note the presence of a parallel sequence red-wards to the MS, which we ascribe to the presence of unresolved binaries

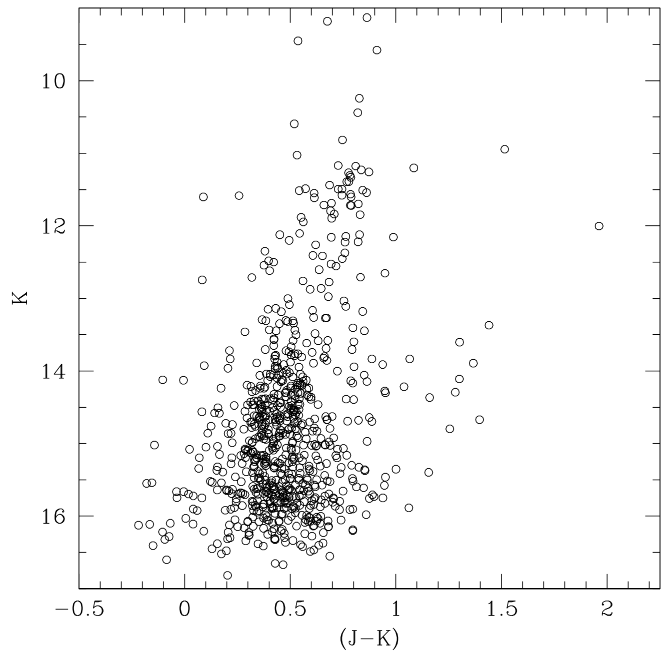


**Fig. 4.** The CMD of NGC 2141 derived from near IR photometry

*3.1. The optical CMD*

The CMD derived from optical photometry is shown in Fig. 2.

The global morphology resembles the CMD of an intermediate age or old open cluster like NGC 7789 (Girardi et al 2000a), IC 4651 (Bertelli et al. 1992) and NGC 2204 (Kassis et al. 1997), say a cluster whose age is between NGC 752 (1.7 Gyr) and M 67 (4.0 Gyr) (Carraro et al. 1999b). The MS extends down to $V \approx 22$, and the Turn Off point (TO) is situated at $V = 15 - 16.5$, $(B-V) = 0.9$, with a few star spreading towards brighter regions ($V \approx 16$). The concentration of stars in the red region of the diagram (at $V \approx 15.0$, $(B-V) \approx 1.5$) represents the Red Giant (RG) clump of core He-burning stars. Note the tilt and the extension of the clump in color, which can be ascribed to a possible spread in metallicity or in age, or to the presence of some differential reddening. The most reasonable explanation is a metallicity effect. Indeed the MS is rather thin up to the limiting magnitude, thus ruling out a significant age dispersion. A secondary sequence of unresolved binary stars is visible on the red side of the MS. This is more evident from Fig. 3, where only the core of the cluster is considered. By counting the number of stars belonging to the two different sequences, we find that the binary percentage amounts as minimum at 30%. Finally, the Herzsprung gap is clearly defined, while the sub-giant and RG branch are scarcely populated.

The population of stars on the right side of the MS and above the TO probably belongs to the field or they might

be blue stragglers which are members of the cluster. The field stars contamination in fact is not very high. The MS is much thinner than in Rosvick (1995) even after the field stars decontamination (see her Fig. 5). This rules out the presence of a significant differential reddening across the $5' \times 5'$ region covered by the present photometry.

### *3.2. The near IR CMD*

The CMD from IR photometry is shown in Fig. 4. The MS extends down to $K = 16.5$, and the TO is located at $K \approx 14.5$, $(J - K) \approx 0.40$. The region above the TO might contain some interlopers (see Fig. 2).
The stars at $K \approx 11.5$, $(J - K) \approx 0.8$ might represent the clump of core He burners. The cluster is indeed faint, and the MS gets rather wide down to $K \approx 15$. The MS is much larger than in the optical CMD, due to the larger photometric errors we have in the IR photometry (see Section 2). Apparently there is no Herzsprung gap, and the RGB is scarsely populated, but sufficiently evident to be used to estimate cluster metallicity (see next Section).

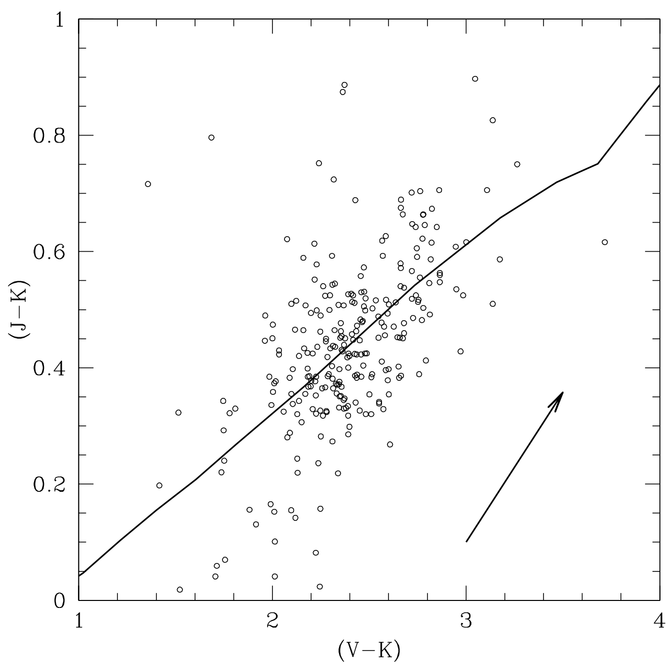


**Fig. 5.** Two colors diagram for MS stars in NGC 2141. The solid line is a Zero Age MS for $[Fe/H] = -0.43$. In the lower right corner the reddening vector is shown. See text for any detail.

## 4. Metallicity

The CMD diagram in the IR allows us to derive an independent estimate of the cluster abundance by using a photometric method (Tiede et al. 1997). This method correlates the slope of the RGB, defined as $\Delta(J - K)/\Delta K$ with the cluster metallicity, measured by the index [Fe/H], and for open clusters, the relation reads:

$$[Fe/H] = -1.639 - 14.243 \times (GBslope). \quad (3)$$

This method has already been applied by us in the study of NGC 7789 (Vallenari et al 2000).
To find the RGB slope we performed a least squares fit to the RGB stars. This yields a RGB slope $\Delta(J-K)/\Delta K$ of -0.085 $\pm$ 0.006. By using the relation (3), we obtain [Fe/H] = -0.43 $\pm$ 0.07. The reported error is derived as:

$$\Delta([Fe/H]) = 14.243 \times \Delta(GBslope). \quad (4)$$

and has to be considered as an optimistic estimate, since it does not take into account the uncertainties in the coefficients of eq. 3, and the sensitivity of the RGB slope to the method adopted for its computation. However the value we find implies a metal content closer to the spectroscopic estimate (-0.39 $\pm$ 0.11, Friel & Janes 1993) than all the other photometric estimates (Janes 1979, Geisler 1987).

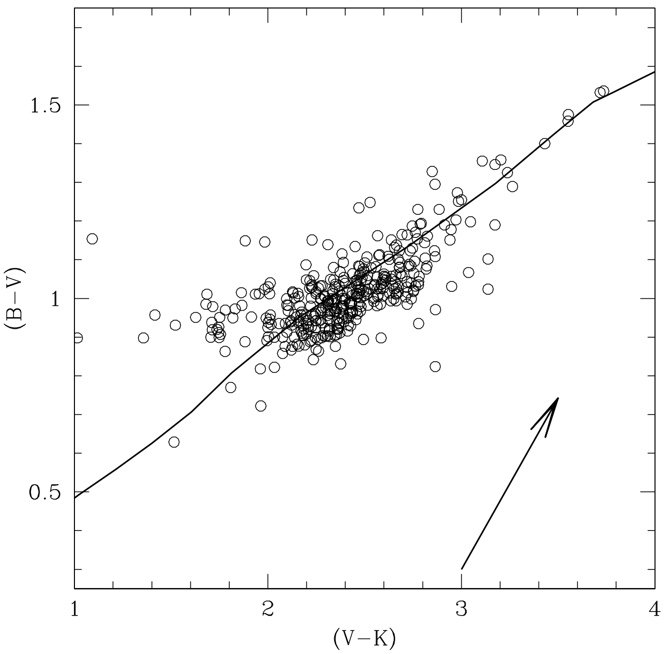


**Fig. 6.** Two color diagram for MS stars in NGC 2141. The solid line is a Zero Age MS for $[Fe/H] = -0.43$. In the lower right corner the reddening vector is shown. See text for any detail.

## 5. Reddening

In order to derive the interstellar extinction for NGC 2141, we have combined optical and IR photometry (500 stars in total), and construct two color diagrams, namely $(J -$

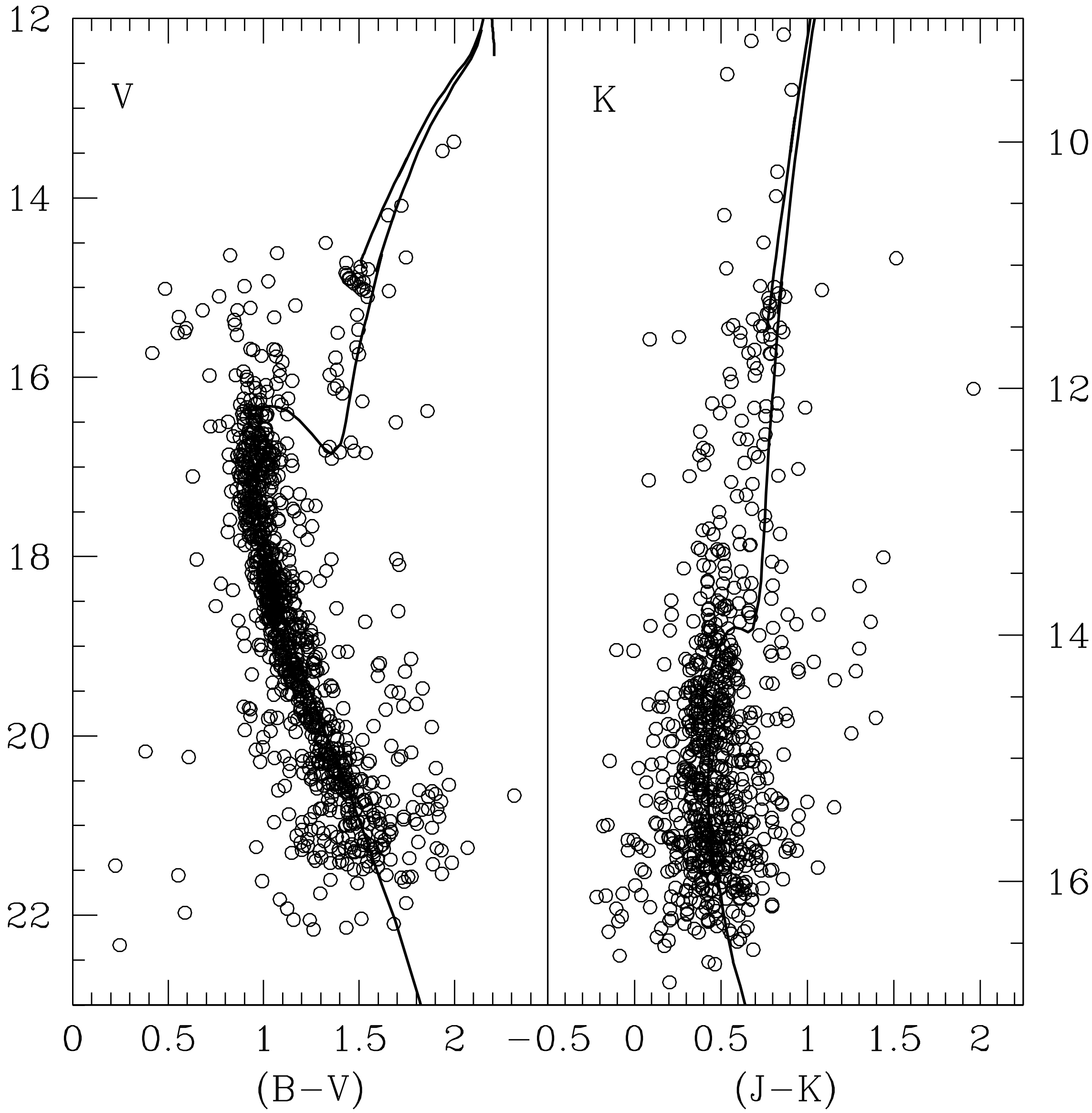


**Fig. 7.** Age determination for NGC 2141. Overimposed on the CMDs are $Z = 0.007$ isochrones for an age of 2.5 $Gyrs$. The right panel shows the fit in the plane $K-(J-K)$, whereas the left panel shows the fit in the plane $V-(B-V)$). See the text for any detail.

$K$) $vs$ $(V-K)$ and $(B-V)$ $vs$ $(V-K)$, which are shown in Fig. 5 and Fig. 6, respectively. Only MS stars are considered to avoid evolutionary effects. We superimposed a Zero Age MS (ZAMS) for the theoretical metal content $Z = 0.007$, obtained translating the observed $[Fe/H]$ by means of the relation:

$$[Fe/H] = \log \frac{Z}{0.019}$$

taken from Girardi et al. (2000b). In Fig. 5 the fit has been obtained by shifting the ZAMS with E(J-K) = 0.07 and E(V-K) = 0.35, which corresponds to a ratio $\frac{E(V-K)}{E(J-K)} = 5.0$, relatively close to the value 5.3 suggested by Cardelli et al (1989).
The fit in Fig. 6, on the other hand, has been achieved by shifting the ZAMS by E(B-V) = 0.40 and E(V-K) = 0.35, whose ratio turns out to be $\frac{E(V-K)}{E(B-V)} = 0.86$, in agreement with the value 0.87 from Cardelli et al (1989). Although reasonable, these estimates are affected by the limitation that the reddening vector is almost parallel to the ZAMS, especially in the $(J-K)$ $vs$ $(V-K)$ plane. This is a minor problem in the plane $(B-V)$ $vs$ $(V-K)$, where we obtain a reddening value E$(B-V)$= 0.40, not much different from E$(B-V)$ = 0.35 derived by Rosvick (1995).

We must stress however that Rosvick (1995) did not take into account the metallicity of NGC 2141, which is lower than the Sun.

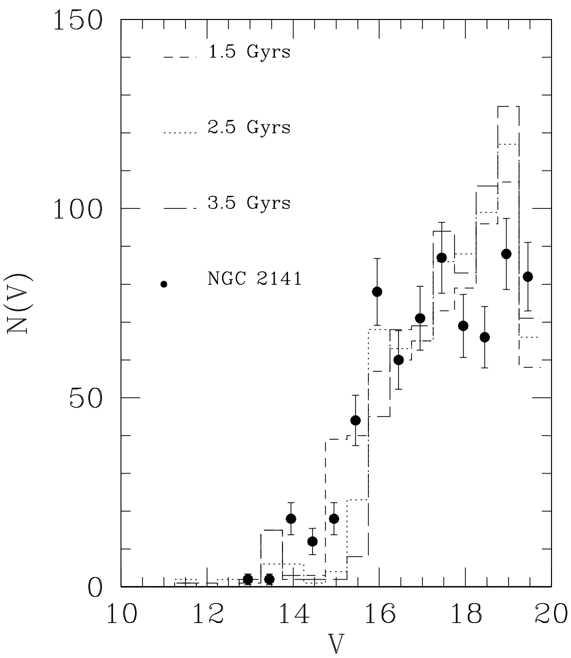


**Fig. 8.** Differential LF of MS stars in NGC 2141 (filled circles). Overimposed are three theoretical LFs for $Z = 0.007$ and ages of $1.5, 2.5$ and 3.5 Gyrs obtained by assuming the Kroupa et al (1993) IMF. See the text for any detail.

## 6. Age and distance

The knowledge of metallicity and reddening, allows us to infer the distance and age of NGC 2141 by means of fitting with isochrones (Girardi et al. 2000b). The fit is shown in the two panels of Fig. 7, for the planes $V$ vs $(B-V)$, and $K$ vs $(J-K)$.

We have adopted the theoretical metallicity $Z = 0.007$ derived above, and performed the fitting with a 2.5 $Gyrs$ isochrone, which better matches the observational data. The criterion that guided us in performing this comparison was the simultaneous fit of the TO and the clump magnitudes. Since no membership exists for this cluster, it is not possible to exactly define the MS TO, which is populated also by unresolved binary stars, and interlopers.

By using the reddening estimated derived in the previous Section, the apparent distance moduli $(m-M)_{K,(J-K)}$ and $(m-M)_{V,(B-V)}$, in the plots turn out to be 13.10 and 14.15, respectively. The latter value can also be obtained assuming that the mean clump magnitude is $M_V = 0.80$ (Girardi et al 1998). Once corrected, these values converge to the absolute distance modulus $(m-M)_o = 12.90 \pm 0.15$. This value is in agreement within the errors with Rosvick (1995) estimate.

NGC 2141 turns out to be $3.8 \pm 0.5$ kpc distant from the Sun, and about 12.0 kpc far from the Galactic Center.

## 7. Luminosity Function

In this section we compute the differential Luminosity Function LF in the V band . The data from the cluster have been previously corrected for completeness (see Carraro & Ortolani 1994 for details). It resulted 100% up to $V = 19$, then 85% at 19.7, 73% at 20.2 and 66% at $V = 20.7$. Fainter bins have not been considered because of the large amount of correction.

This LF is compared in Fig. 8 with thoretical ones for the same age range (1.5, 2.5 and 3.5 Gyr) and metallicity (z=0.007) of NGC 2141. The theoretical LFs have been calculated by assuming the IMF proposed by Kroupa et al (1993), which is somewhat steeper than the classical Salpeter (1955) IMF , and best suited for the Solar Neighbourhood. It reads:

$$\Phi(M) = \begin{cases} C_{k1}\, M^{-0.5} & M < 0.5 \\ C_k\, M^{-1.2} & 0.5 < M < 1 \\ C_k\, M^{-1.7} & M > 1 \end{cases}$$

where $C_{k1} = 0.48$ and $C_k = 0.295$.

The comparison clearly shows that the agreement with theoretical models is good up to $M_V = 5.0$ . At fainter luminosities the theoretical models predict a higher number of stars, increasing with decreasing magnitudes. This occurs in the main sequence at about 1.0 $M_\odot$, while the TO corresponds to about 1.4 $M_\odot$.

It seems more reasonable to interpret these data as a more common mass segregation effect with low mass stars evaporated from the cluster center.

## 8. Conclusions

In this paper we have presented a detailed study of the poorly known intermediate age open cluster NGC 2141. By combining optical and IR photometry we have proved that NGC 2141 is a moderate age open cluster about 3 $Gyr$ old, intermediate in age between the NGC 752 and M 67.

By studying the color magnitude and two color diagrams, we have obtained estimates for the cluster metallicity, reddening and distance. In detail, we found that the color excesses E$(J-K)$ and E$(B-V)$ are 0.07, and 0.40, respectively, and that their ratios are in agreement with the standard values (Cardelli et al 1989). The derived corrected distance modulus $(m-M)_o = 12.90$ implies a distance of 3.8 kpc from the Sun.

These findings are supported by the comparisons of the cluster LF with theoretical ones, from which we find also evidences of mass segregation below $M = 1.0 M_\odot$.

*Acknowledgements.* This study has been financed by the Italian Ministry of University, Scientific Research and Technology (MURST) and the Italian Space Agency (ASI).

## References

Bertelli G., Bressan A., Chiosi C., 1992, ApJ 392, 522
Burkhead, M.S., Burgess R.D., Haisch B.M., 1972, AJ 77, 661
Cardelli J.A., Clayton J.C., Mathis J.S., 1989, ApJ 345, 245
Carraro G., Ortolani S., 1994, A&AS 106, 573
Carraro G., Vallenari A., Girardi L., Richichi A., 1999a, A&A 343, 825
Carraro G., Girardi L., Chiosi C., 1999b, MNRAS, 309, 430
Carraro G., Vallenari A., 2000, A&AS 142, 59
Friel E.D., 1989. PASP 101, 244
Friel E.D., Liu T., Janes K.A., 1989, PASP 101, 1105
Friel E.D, Janes K.A., 1993, A&A 267, 75
Geisler D., 1987, AJ 94, 84
Girardi L., Groenewegen M.A.T., Weiss A., Salaris M., 1998, MNRAS 301, 149
Giraldi L., Mermilliod J.-C, Carraro G., 2000a, A&A 354, 892
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000b, A&AS 141, 371
Hunt L.K., Mannucci F., Testi L., Migliorini S., Stanga R.M., Baffa C., Lisi F., Vanzi L., 1998, AJ 115, 2594
Janes K.A., 1979, ApJ S 39, 135
Kassis M., Janes K.A., Friel E.D., Phelps R.L., 1997, AJ 113, 1723
Kroupa P., Tout, C. A., Gilmore G., 1993, MNRAS 262, 545
Landolt A.U.,1992, AJ 104, 340
Minniti D., 1995, A&AS 113, 299
Rosvick J.M., 1995, MNRAS 277, 1379
Salpeter E.E., 1955, ApJ 129, 608
Tiede G.P., Martini P., Frogel J.A., 1997, AJ 114, 694
Vallenari A., Richichi A., Carraro G., Girardi L., 1999, A&A, 349, 825
Vallenari A., Carraro G., Richichi A., 2000, A&A, 353, 147

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.